Determining Hybrid Reflectance Properties and Shape Reconstruction by using Indirect Diffuse Illumination Method

*Tae-Eun Kim and **Jong-Soo Choi

*, **Department of Electronic Engineering, Chung-Ang University
221 Huksuk-dong, Dongjak-ku, Seoul, 156-756, KOREA
E-mail : kte@candy.ee.cau.ac.kr

Abstract

In this paper, we propose the estimating method of reflectance properties and the recovery of shape by using Normal Sampler and Indirect Diffuse Illumination Method(IDIM). Photometric Stereo Method(PSM) is generally based on the direct illumination. PSM in this paper is modified with indirect diffuse illumination(IDI) and then applied to hybrid reflectance model which consists of two main components; Lambertian and specular reflectance. Under the indirect diffuse illumination, the reflectance properties of natural objects can be determined by using Normal Sampler that has almost all the normal components in the observed direction. The estimated reflectance properties are used to construct reference table. Also, 3-D shape of an object can be recovered from intensity distribution of a pixel and a reference table. In this paper, the reference table is used to recover the 3-D shape of an object and IDI simplifies the limited conditions of reflectance analysis for prior studies without any loss in performance. The proposed method can be applied to various types of surfaces which can be defined by hybrid reflectance.

1. Introduction

In machine vision, extracting the 3-D shape information from image intensities is an important issue. Image brightness is dependent on surface orientation, reflectance properties, and image acquisition device including the lighting condition. To reconstruct the shape from shading, it is generally assumed that the surface reflectance is homogeneous. However, additional assumptions about the surface reflectance is needed to make the problem more tractable. For example, the most common assumption is that the surface of an object obeys the Lambertian reflectance. Unfortunately, most real surfaces are neither specular nor perfectly diffuse. Nayar et al.[1] demonstrated the importance of understanding the reflectance properties of surface in the shape recovery.

Depending on the roughness characteristics, the surfaces can be classified as three different groups: diffuse, specular, or hybrid[2]. Many surfaces are observed to be hybrid in the real-world. The hybrid reflectance model is able to control the degree of reflection by the surface roughness parameter and the ratio of diffuse and specular components. Thus, the hybrid reflectance model is, in fact, a linear combination of diffuse and specular components, and it can be applied to the surfaces with varied reflectance characteristics. In this paper, based on the hybrid reflectance model[1,2], we present non-iterative 3-D shape recovery algorithm, which is very simple and fast as compared with the conventional iterative algorithms[3,4]. Especially, we focus on the objects with a hybrid reflectance surface, since these objects are important in industrial applications, such as plastic, electric parts, and coin surfaces. The research, the shape recovery for the hybrid reflectance surface, has been actively studied in recent years[2,4,5]. To solve the 3-D shape recovery problems, Bakshi proposed the General Shading Logic algorithm(GSL)[5] in which the surface was assumed to be smooth and the intensity variation among adjacent pixels was assumed to be small. That model had a lot of restriction with respect to the surface reflectance property , and the limit that the surface of the target object is a smoothly sloped surface. Thus, in this paper we propose the estimating method of reflectance properties and recovery of shape by using Indirect Diffuse Illumination (IDI) and Normal Sampler. The Indirect Diffuse Illumination Method(IDIM) is used to avoid specular spike and highlight which usually cause intensity disparities. It is easy to irradiate a shiny portion using IDIM since the shining of a target surface can be reduced by using a uniform and non-directional light reflected from the disk-type surface. The estimated reflectance properties are used to construct a reference table and shape ecovery. The proposed method has been successfully applied to a number of synthetic and real objects.

2. Indirect Diffuse Illumination Method

2.1 Geometric optics model for Indirect Diffuse Light Source

A geometric optics model of a disk-shape light source is shown in Fig. 1. When a point light source is projected on the disk-shape diffuse surface, the distance

---

This work is supported in part by the Eng. Research Center for Advanced Control and Instrumentation (ERC-ACI) in Seoul National Univ. by KOSEF.

between the point light source and a point *P(r, ϕ)* is denoted by *d* and the interval angle between the normal vector at *P(r, ϕ)* on the disk and the incident angle of the point light source is θ. The intensity, $I_{disk}(r, \phi)$, at an arbitrary point of the disk-type surface is derived from the geometric optics model structure as follows.

$$I_{disk}(r,\phi) = \frac{I_p \cdot k_d \cdot d'}{\left(d'^2 + (r\cos\phi - R\cos\Phi)^2 + (r\sin\phi - R\sin\Phi)^2\right)^{3/2}} \quad (1)$$

where, *Ip* is strength degree of the light source, *Kd* is the Albedo constant.

2.2 Surface reflectance function derivation

To determine the amount of the light caught through a camera, the surface reflectance property of a target object, the surface slope of a target object, the disk-light direction, the distance between a disk-light and a target object, and the light energy flux emitted from a light *P(r, ϕ)* must be known when the light *P(r, ϕ)* on the disk-type light source is irradiated to the target object. The surface of the target object has two reflectance properties; the Lambertian reflectance and the specular reflectance. The intensity of the shading image *(I)* at a point on an object surface can be represented as

$$I = I_{spec} + I_{diff} \quad (2)$$

where I_{spec} is the specular reflectance and I_{diff} is the Lambertian reflectance.

The brightness at a point on the Lambertian reflectance surface is proportional to the incident light energy flux when a point source is irradiated on the Lambertian reflectance surface.

$$I_{diff} = k_L \overline{s} \cdot \overline{n} \quad (3)$$

where $\overline{s}$ is the unit vector along a point source direction, $\overline{n}$ is the unit normal of the Lambertian reflectance surface, and k_L is the surface Lambertian reflectance constant.

Torrance-Sparrow model[6] which satisfies the specular reflectance condition is generally used. The specular reflectance intensity I_{spec} in the specular reflectance model with respect to a point source can be written as

$$I_{spec} = B\exp\left(\frac{-\alpha^2}{2\sigma^2}\right), \quad (4)$$

where the surface's roughness σ is the standard deviation of Gauss distribution function and α is the angle between the specular direction and the surface normal direction. The large value of σ means that the directions among adjacent facets are very variations and the small value of σ means that the facets are located in almost the same direction. The specular reflectance rate B can be represented as $B = K_s F G$. Where *F* is the Fresnel reflection coefficient, *G* is the geometrical attenuation factor and K_s is the constant to normalize the surface reflectance property.

When three point sources (S1, S2, S3) located at intervals of 120 degrees are irradiated, in order, on the disk, this disk becomes the Indirect Diffuse Illumination(IDI) shown at Fig. 2. The amount of the light at a point *p(r, ϕ)* on the disk-light, IDI, is determined by the distance between a point *p(r, ϕ)* and a point source, and a point source's flux. When the light at a point *p(r, ϕ)*, IDI, is irradiated on the object, the intensity at a point on the object's surface is determined by the object's surface direction, the distance between the object and the light at a point *p(r, ϕ)*, and the light flux at a point *p(r, ϕ)*. The terms, tilt and slant, represent the object's surface slope. The IDI's direction S_{tilt} and S_{slant} are written as $S_{tilt} = \phi$, $S_{slant} = \tan^{-1}(\frac{r}{D})$. The camera is located at the center of the disk-light. The distance *ds* between a point *p(r,ϕ)* and a point on the object is written as $d_s = \sqrt{D^2 + r^2}$ where *D* is the distance between the camera and the object and *r* is the distance between the camera and the light at a point *p(r,ϕ)*. The light flux *I'* at a point *p(r,ϕ)* can be written as

$$I' = \frac{I_{disk}(r,\phi)\cdot\cos(S_{slant})}{d_s^2}, \quad (5)$$

where $\cos(S_{slant}) = \frac{D}{d_s}$.

3. The analysis of hybrid reflectance and the extraction of its properties

The above-mentioned equations are defined as follows :

$$I' = \frac{I_{disk}(r,\phi)\cdot\cos(S_{slant})}{d_S^2}$$

where, $S_{slant}(\theta) = \arctan(r/D)$, (6)

$d_S = \sqrt{D^2 + r^2}$ and $S_{tilt} = \phi.$

Thus, irradiance(E) of disk-light is obtained by integration ;

$$E = \int_0^R \int_0^{2\pi} I'(r,\phi) r dr d\phi . \quad (7)$$

A light is projected on the object surface and we use the hybrid reflectance properties as the Torrance-Sparrow Model[6]. Therefore, the intensity *I* on a pixel of the target object can be represented as ;

$$I = I_{diff} + I_{spec} = k_L \bar{n}\cdot\bar{s} + k_s \frac{1}{\sqrt{2\pi\sigma}}\exp\left(-\frac{\alpha^2}{2\sigma^2}\right),$$
$$k_L + k_s = 1, \quad (8)$$

where k_L is the Lambertian reflectance constant, k_S is the specular reflectance ratio, and surface roughness is

σ.

The intensity on a surface point (**I**) is represented in the following matrix form

$$\mathbf{I} = k_L \mathbf{N} \cdot \mathbf{S} + k_S \mathbf{a}, \qquad (9)$$

where **I** is the Intensity value , **S** is the Light source direction , **N** is the Surface normal, and **a** is the specular direction vector including the exponential term denoted by α. The above equation becomes a nonlinear simultaneous equation with three unknown variables; k_L, k_S, and σ. We can get some surface normals by using the Normal Sampler shown in Fig. 3. The Normal Sampler consists of tilt scale on the bottom and slant scale beneath the table. A small flat-plate is depositted on the table. The three point sources are turned on in order. The small flat-plate has one directional normal. We already know the normal vector of flat-plate , three intensity values (I1, I2, I3), and the position vectors of three point sources (s1, s2, s3). As the Normal Sampler is adequately manipulated, we can obtain three shading images. The intensity *I* at a point of the small flat-plate is represented in the above equation(eq.8). It can measure the normal of a flat surface which consists of the same materials as the object of interest. We can solve the equation using three light sources by using the numerical analysis method. Fig. 2 approximately shows our proposed system. Fig. 9 shows the extraction result for the reflectance properties of the target object by the proposed method.

4. The making of the reference table for shape reconstruction

A Reference table is used to find the surface normal of the target object. It can be made by applying determined properties to a sphere image. And the reference table shows the relation between the surface normal and its intensity. The considered factors are the rate of specular reflectance(k_S), the rate of Lambertian reflectance(k_L),andthe surface roughness characteristics(σ). The fittest normal can be selected for the object point obtained by IDI. Fig. 4 shows the reference table obtained by using the IDI.

5. Estimation of proposed algorithm

Fig. 5 illustrates the shading images used for the experiment. To estimate our algorithm performance, we applied our algorithm to the superellipsoid image which was used in Bakshi's General Shading Logic algorithm[5], where k_s and $k\ (=1/2\sigma^2)$ in the image have the same value of that algorithm. We apply the surface reflectance function to the data which were used in Bakshi's model. We obtain three shading images for the data. Fig. 6 illustrates the three dimensional image that was reconstructed by the proposed algorithm.The relative error angle for the superellipsoid is about three degrees in Bakshi's GSL algorithm[**5]**. However, in our algorithm, the relative error angel for the superellipsoid is about one degree[4,5].

6. The real image used in the experiment

The Hybrid Surface Reflectance Function is applied to the real intensity image. Three intensity images, where specular ratio k_S is 0.61, surface roughness $k(=1/2\sigma^2)$ is 10.2, and the interval degrees of lighting sources is 120°, and the three shading images are shown as Fig. 7.

6.1. The results of the experiment

If the three intensity images which were obtained by IDI of the different source positions are inputted, the normal vector can be determined by comparing each intensity with the reference table, which is made by determined parameters(k_S,k_L,σ). Fig. 8 shows the recovered surface normal vector.

7. Conclusions

In this paper, we suggest that the surface reflectance function should be suitable for the established indirect diffuse illumination environment. The proposed method makes it possible to determine the reflection properties of the hybrid reflectance surface and to recover the shape of such surface accurately and rapidly using the reference table. Finally, the experimental results show that the performance of this algorithm is superior to that of the existing methods [2,4,5]. In the future studies, we will carry out the experiment for various objects by using IDI. In order to apply our model to the industry fields, we will analyze the surface reflectance property, the surface reflectance ratio, and make the 3-D reference table with respect to various objects.

References

[1] S. K. Nayar, K. Ikeuchi, and T. Kanade, "Surface Reflection : Physical and Geometrical Perspectives",*IEEE Trans. PAMI.*., vol. 13, no. 7, pp. 611-634 31, July 1990

[2] T. E. Kim and J. S. Choi , "Shape Reconstruction of Hybrid Reflectance Object Using Indirect Diffuse Illumination, " *IEICE Trans. Inf. & Syst.*, vol . E78-D, no.12, pp. 1581-1590, December 1995.

[3] B. K. P. Horn, "Understanding Image Intensities," *Artificial Intelligence*, vol. 8, pp. 201-231, 1977

[4] S. K. Nayar K. Ikeuchi and T. Kanade, "Determining Shape and Reflectance of Hybrid Surfaces by Photometric Sampling", *IEEE Trans. Robotics and Automation*, vol. 6, no. 4, pp. 418-431, August 1990.

[5] Sanjay Bakshi, Y. H. Yang, "Shape from Shading for Non-Lambertian Surfaces," *in Proc. IEEE ICIP-94*, vol. II, pp. 130-134, Austin Texas, Nov. 1994

[6] K. E. Torrance and E. M. Sparrow, "Theory for off-specular reflection from roughened surface for ray reflection," *Journal of Optical Society of America*, vol.

65, pp. 531-536, 1975

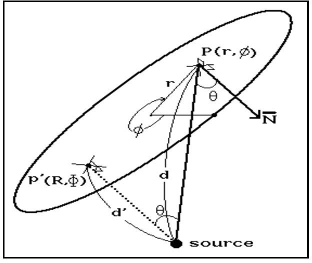


Fig.1.Geometric optics model of Disk-Shape Light source

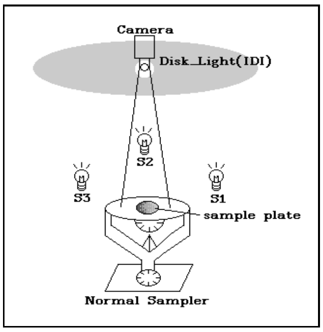


Fig. 2. Image formation model by IDI

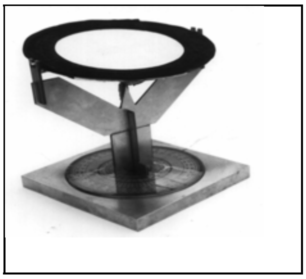


Fig. 3. Normal Sampler

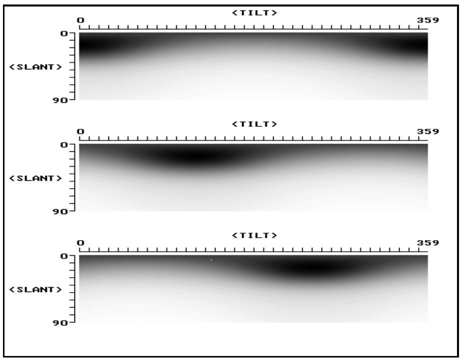
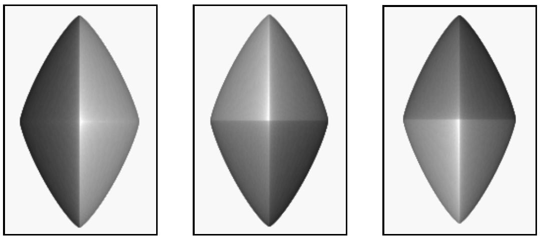
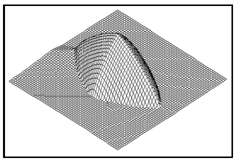


Fig. 4. The reference table by IDI (*ks=0.61*, $1/2\sigma^2=10.2$)



Superellipsoid (k_s=0.5, $k=1/2\sigma^2=10$)

Fig. 5 Shading images were obtained by using the surface reflectance function.



Superellipsoid(k_s=0.5, k=10)

Fig. 6 Reconstructed 3-D images.

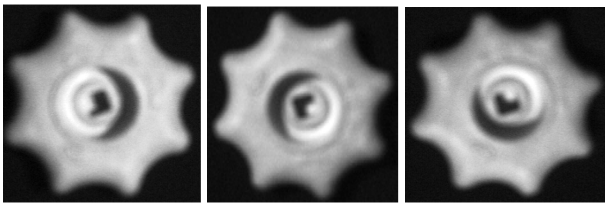


Fig. 7. Real intensity image of NUT (*ks*=0.61, $1/2\sigma^2$ =10.2)

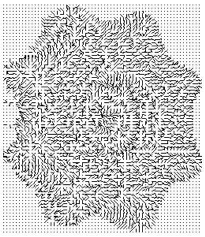


Fig.8. The recoverd needle map(NUT)

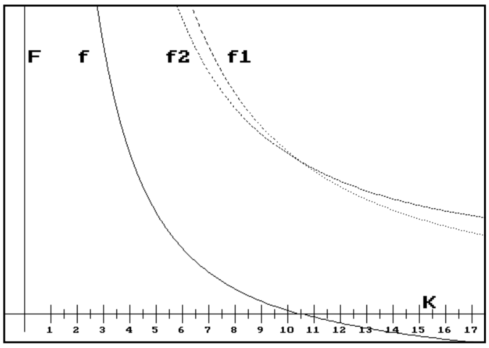


Fig.9 Reflectance properties of NUT (ks=0.61, $1/2\sigma^2$ =10.2)